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INTEGRATED POWERHEAD DEMONSTRATION
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Abstract

The Integrated Powerhead Demonstration (IPD) is a 1,112,000 N (250,000 lb_f) thrust (at sea level) LOX/LH2 demonstration of a full flow cycle in an integrated system configuration. Aerojet and Rocketdyne are on contract to the Air Force Research Laboratory to design, develop, and deliver the required components, and to provide test support to accomplish the demonstration. Rocketdyne is on contract to provide a fuel and oxygen turbopump, a gas-gas injector, and system engineering and integration. Aerojet is on contract to provide a fuel and oxygen preburner, a main combustion chamber, and a nozzle. The IPD components are being designed with Military Spaceplane (MSP) performance and operability requirements in mind. These requirements include: lifetime $\geq$ 200 missions, mean time between overhauls $\geq$ 100 cycles, and a capability to throttle from 20% to 100% of full power. These requirements bring new challenges both in designing and testing the components. This paper will provide some insight into these issues. Lessons learned from operating and supporting the space shuttle main engine (SSME) have been reviewed and incorporated where applicable. The IPD program will demonstrate phase I goals of the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program while demonstrating key propulsion technologies that will be available for MSP concepts. The demonstration will take place on Test Stand 2A at the Air Force Research Laboratory at Edwards AFB. The component tests will begin in 1999 and the integrated system tests will be completed in 2002.

INTRODUCTION

The Integrated Powerhead Demonstration (IPD) program was developed to integrate and exploit technologies which have been developed since the design of the Space Shuttle Main Engine (SSME) . The IPD program is the only technology program in place which directly supports a new, fully reusable engine. This program was established to develop and demonstrate key propulsion technologies which would enable long life, high performance, and reduced maintenance.

TECHNOLOGIES INCREASE OPERABILITY

The main purpose of the IPD program is to develop technologies to enable a propulsion subsystem which would meet military spaceplane requirements. This vehicle would have to be capable of high sortie rate and surge requirements, rapid turnaround time, and be able to fly pop-up and once around missions. This vehicle is still in the concept phase so the technologies developed and demonstrated in the IPD program must be applicable to as many military spaceplane concepts as possible. Keeping this in mind, the IPD contractors were constrained to utilize liquid oxygen (LOX) and liquid hydrogen (LH_2) as propellants, providing traceability to a single-stage-to-orbit vehicle. In addition, the contractors were directed to adopt a full flow staged combustion cycle to insure high engine specific impulse and provide low turbine temperatures to boost engine life. The most stressing case of all the potential MSP concepts incorporated a vertical landing vehicle. This concept would require a propulsion system with an ability to throttle

down to low power levels (to allow for a soft landing). The engine would also have to be restarted in order to land the vehicle safely. Accordingly, the IPD contractors were asked to develop restartable designs capable of throttling down to 20% of sea level design thrust.

With the above requirements in mind (LOX/LH_2, full flow cycle, deep throttling, and restartable), Rocketdyne was contracted to do a system engineering study in which a thorough analysis of the Space Shuttle Main Engine (SSME) was conducted. Results from this comparative analysis identified priority areas on which the IPD could focus. An optimized engine operating point was then selected to minimize engine and launch vehicle lifecycle costs. The resulting optimized engine design became the basis on which requirements for each of the various components were flowed down to the various design organizations.

Comparative Analysis

The SSME represents the state-of-the-art in reusable launch vehicle propulsions systems, so a lessons learned study was put together to understand what was working well and to identify where improvements could be made. This study was performed by consulting engineers, mechanics, and technicians responsible for maintaining the SSME. As a result, a total of 51 operations and support drivers were identified. These drivers were rated based on their impact on program cost and schedule, and prioritized from high impact to low impact. Turbopump life was identified as the number one SSME driver: it ranked high in turnaround time, high in turnaround labor, high in hardware spares cost, and high in flight support labor. Solving this problem for reusable rocket engines is one of the major goals of the IPD program.

Once it was established that the turbopumps were of primary interest to the IPD program, a similar study was done which identified the major factors which limited their lifetime. Bearing wear was the most significant contributor to reduce turbopump lifetime. NOTE: (This data is based on Rocketdyne experience with the original bearings. Data on the wear performance of the silicon nitride ball bearings is still being compiled.) Turbine blade cracking and high inspection requirements were also significant factors in limiting lifetime.

To reduce the impact ball bearings have on the rotating machinery the IPD program has incorporated hydrostatic bearings in the turbopump designs. The concept of the hydrostatic bearing is that the rotating shaft is supported on a layer of pressurized fluid. This eliminates metal to metal contact under normal operating conditions and theoretically provides unlimited life. Since there are no bearings to limit the speed of the shaft, higher shaft speeds can be achieved. This provides the designer with an option of reducing the diameter of the turbine and impellers to save weight.

Selection Of Full Flow Engine Cycle

The full flow engine cycle was selected to increase the life of the turbines. Damaged and cracked blades, resulting from exposure to a severe thermal environment, was a significant life limiting factor. To increase the life of the blades a solution was identified which reduced the temperature of the hot gases used to drive the turbines. Turbine power is a function of mass flow rate and temperature:

$$\text{Turbine Power} = \dot{m} C_P \eta \Delta T$$

where $\dot{m}$ = mass flow rate, C_P = specific heat at constant pressure, η = turbine efficiency, and ΔT = change in temperature.

In the full flow engine cycle, the mass flowrate term in the aforementioned equation is increased by forcing all of the available propellant (fuel and oxidizer) through the turbines driving the pumps. This approach contrasts with the SSME which utilizes fuel rich gas to drive both the oxygen and hydrogen turbopumps. As a result only 20% of the available mass flow is available to drive the turbopumps. The mass flow is increased in the full flow cycle by utilizing both a fuel rich and an oxygen rich preburner, each driving their respective turbopump. As a result, an engine power balance can be attained at lower turbine inlet temperature and the life of the turbines and other hot gas system components is enhanced. A schematic comparison of the SSME fuel-rich staged combustion cycle to the full flow cycle is provided in Figure 1.

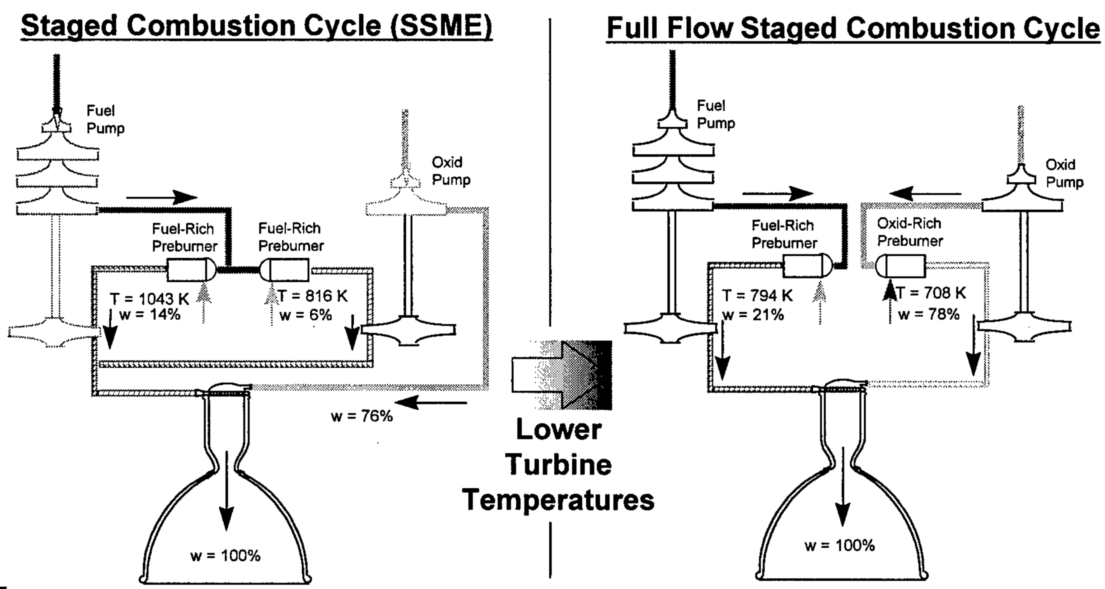


FIGURE 1. Staged Combustion Cycle (SSME) vs Full Flow Staged Combustion Cycle

The lower hot gas system temperatures also provide a number of other benefits to the engine design. One benefit is the fact that the turbine designer can select from a wider range of potential materials including candidates that are compatible with their respective operating environments and do not require coatings for protection. Lower turbine temperatures also eliminate the need for cooled hot gas ducting and can reduce the associated sheet metal low cycle fatigue problems . Since the oxygen turbine is now driven by an oxygen-rich gas rather than a fuel-rich gas, a critical interpropellant seal is eliminated. This seal was previously required to ensure the LOX in the pump end of the oxygen turbopump and the fuel-rich gas driving the turbine never mixed, to cause a catastrophic failure.

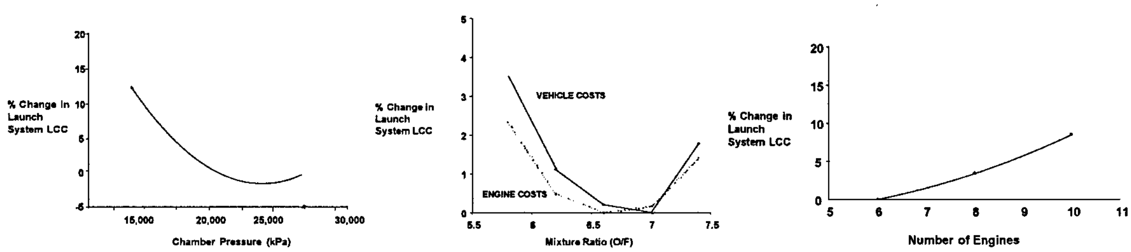
To realize these benefits in the turbopumps, other components would have to be specially designed. These include an oxygen preburner and a hydrogen preburner to provide hot gases to each of the turbines and a gas-gas injector that will mix the gases prior to combustion in the main combustion chamber.

Rocketdyne is under contract to design and fabricate the fuel and oxygen turbopumps and Aerojet is under contract to design and fabricate the fuel and oxygen preburners. Also, to enable demonstration of these components in a full flow cycle engine configuration, Rocketdyne is designing and building a gas-gas injector with flight-type elements which is being delivered as special test equipment. Along the same lines Aerojet is responsible for designing and fabricating a main combustion chamber and a nozzle as special test equipment. Rocketdyne has

responsibility for system engineering and integration of all of the components for the demonstration.

<u>Optimization Of Engine Operating Point</u>

To select the operating points that the components would be designed to, a system engineering study was done. In this study, Life Cycle Cost (LCC) of the final system was traded against varying values of key design parameters. These parameters were: chamber pressure, mixture ratio, and number of engines. The results of this study are shown below in Figure 2.



a. b. c.

FIGURE 2. Parametric curves representing Life Cycle Cost (LCC) versus Chamber Pressure, Mixture Ratio, and Number of Engines.

It was shown, Figure 2a, that LCC was substantially reduced as chamber pressure increased to 22,408 kPa (3250 psia) . From 22,408 kPa (3250 psia) to 27,580 kPa (4000 psia) the curve is relatively flat, with minor increases starting to become evident above 27,580 kPa (4000 psia). The reason for this increase above 27,580 kPa (4000 psia) is due to increased engine complexity which tends to drive both developmental costs and vehicle size up. Since the value added versus design difficulty was small above chamber pressures of 20,685 kPa (3000 psia) it has been determined that IPD components should be designed to 20,685 kPa (3000 psia).

The mixture ratio (oxygen/fuel) was similarly studied and two curves are shown in Figure 2b. One is mixture ratio optimized to reduce LCC of the engine, and the other is to reduce LCC of the vehicle. As mixture ratio increases, the size of the propellant tanks gets smaller which reduces vehicle size and drives LCC down. Once the mixture ratio hits 6.6, thermal margins and reliability issues overcome the size issue for the engine and start to drive LCC up. However, from a vehicle standpoint this does not occur until a mixture ratio of 7.0 is obtained. Taking these issues into consideration the IPD components are being designed to a mixture ratio of 6.7.

The number of engines was optimized based on a requirement that the lift-off thrust-to-weight (T/W) of the vehicle be maintained greater than 1.05 with one engine not operating. The resulting curve, Figure 2c, shows that LCC is reduced as the number of engines is reduced. This is due to the increased cost of unreliability that arises as more engines are used. When fewer than six engines are used, the increased T/W requirements and resulting launch vehicle growth counter any benefits seen from the reduced reliability requirements. This analysis was considered, along with the cost of actually performing a demonstration. It was determined that the components would be designed and tested at a thrust level of 1,112,000 N (250,000 lb_f)of thrust. The technologies being incorporated would be scaleable from 355,840 N (80,000 lb_f)of thrust to 1,779,200 N (400,000 lb_f)of thrust. This would also produce a meaningful demonstration of a booster sized engine while keeping facility costs of operating the facility to a minimum.

To maintain the long life, increased operability requirements that formed the basis for this program in the first place, all components are being designed to Mean Time Between Overhauls (MTBO) of 100 cycles. One cycle is equal to one start-operate-shut down sequence.

TECHNOLOGIES LEAD TO INCREASED PERFORMANCE

High performance must be delivered by future launch vehicle propulsion systems in order to meet increasingly demanding requirements and ultimately keeping operational costs affordable. IPD technologies provide increased performance as identified in Figure 3.

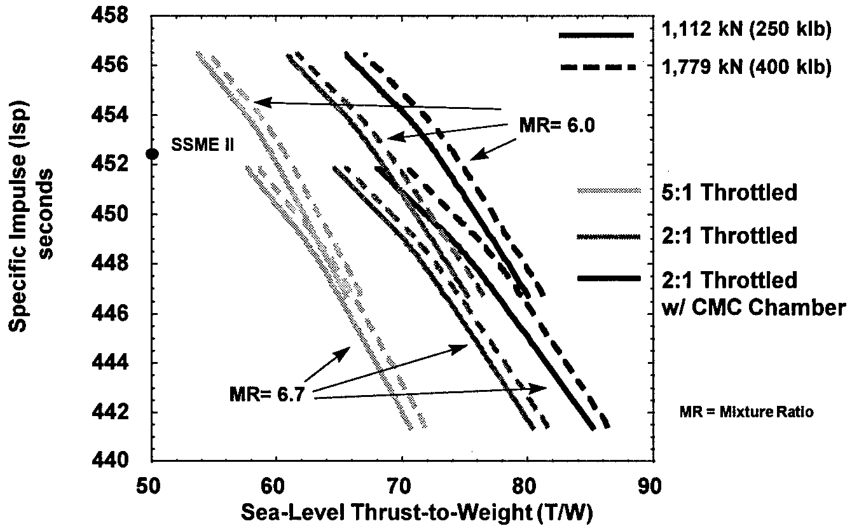


FIGURE 3. Performance of IPD derived engines.

This series of curves represents how (T/W) and specific impulse (Isp) can be traded in a flight engine that incorporates IPD technologies. The solid curve in the lower left corner represents an IPD derived engine capable of deep throttling and operating at a mixture ratio of 6.7 and delivering 1,112,000 N (250,000 lb_f) of thrust. The bottom data point represents a T/W of approximately 71 and an ISP of 441. This data point is for a bell nozzle with an expansion ratio of 50:1. As the expansion ratio increases T/W and sea level performance are traded for Isp. The dashed line immediately to the right represents the same engine delivering 1,779,200 N (400,000 lb_f)of thrust. Two additional sets of curves are provided to the right of the baseline IPD engine data. The first curve represents an IPD derived engine that does not incorporate deep throttling. The increase in T/W for this engine is directly related to the fact that valves required to direct flow of gases around the turbines are no longer required. Finally the pair of curves in the lower right represent an IPD derived engine utilizing a ceramic matrix composite combustion chamber which would further reduce the weight of the engine.

The upper series of curves directly above the lower set represents how Isp can be increased by reducing the mixture ratio from 6.7 to 6.0.

TECHNOLOGIES DEMONSTRATED IN AN ENGINE CYCLE

The IPD components will be tested on Test Stand 2A at the Air Force Research Laboratory, located on Edwards AFB, CA.

The preburners will be the first components tested. They will be characterized using vaporized propellants which will be provided by the facility. Construction of the facility will involve the development of an oxygen vaporizer to produce gaseous oxygen at near ambient temperature from LOX. The fuel preburner will have a maximum test duration of 6.0 seconds at main-stage conditions and the oxygen preburner will have a maximum duration of 8.5 seconds at main-stage conditions. The preburners will be characterized individually with approximately 25 tests on each one, and then both will be connected to the injector assembly and an ablative main combustion

chamber. These tests will demonstrate Aerojet's platelet technology which allow fine, dense element injector patterns to be made which in turn improve mixing, atomization, combustion and injector face cooling. These attributes, coupled with a basic design concept similar to the Russian NK33 engine oxygen preburner, allow the IPD oxygen preburner to meet the operational requirements while not relying on coatings to meet required life.

The injector test series with the ablative chamber will consist of 8 tests of approximately 4.0 seconds each in duration. Following completion of that test series, the main combustion chamber and nozzle will be connected to the injector and the entire thrust chamber assembly will be tested. The injector incorporates flight-type elements in a gas-gas configuration, and also will demonstrate Rocketdyne's laser ignition technology that is being used to ignite the propellants. The IPD Engine Main Combustion Chamber (MCC) incorporates Aerojet's Formed Platelet Liner technology. This technology allows the use of conventional materials to produce a flight weight hydrogen cooled liner that can have a life in excess of 200 cycles while requiring a minimal pressure drop allocation. The IPD oxygen cooled nozzle serves as a gasifier for the LOX prior to entering the oxygen preburner. The nozzle also makes use of Aerojet's Formed Platelet Liner technology to produce an efficient, cost effective, heat exchanger of a flight weight design. The maximum duration of these tests will be approximately 5.0 seconds. During this test series, vaporized propellants for preburner operation will be provided via the cooling circuits built into the nozzle and MCC.

Initial testing of the turbopumps can be conducted in parallel to the thrust chamber activity. Each turbopump will be tested using an ambient temperature turbine drive fluid to first verify the mechanical integrity of the pump and turbine, and to demonstrate the performance of the pump. The IPD turbopumps will demonstrate hydrostatic bearing technology as well as material developments which coupled with the full flow cycle enable high performance and long life. This series will incorporate approximately 10 tests for each turbopump, will be run at various power levels from 20% to 100%, and range in duration from 5 to 25 seconds depending on the test. Following completion of that test series, the fuel preburner will be connected to the turbine inlet of the fuel turbopump and 10 more tests will be performed using hot drive gases. The maximum duration of the turbopump at main-stage condition is 5 seconds.

Once the performance of all the components has been adequately defined, all the aforementioned components will be removed from the test facility, transported to an assembly area, and assembled into an engine configuration. The assembled engine will then be transported back to the test area, reinstalled in the test stand in a horizontal position, and subjected to a series of system level tests. It is anticipated that approximately 60 initial start-stop tests will be conducted to develop and verify the engine start and shutdown sequences. After the engine transients have been adequately characterized, a series of approximately 30 full duration tests is planned to map engine performance. These tests will include engine operation at various throttle settings, mixture ratios, inlet conditions, and turbine temperatures. These full duration tests are expected to last on the order of 30 seconds.

Acknowledgments

Air Force Phillips Laboratory Military Spaceplane Technology Office in Albuquerque, NM

References

Csomar, A. (1995), "Integrated Powerhead Demonstrations Program Subsystem Design Analysis Report.", Rocketdyne

IPD Operations & Logistics (1995), "Operations & Logistics Support Comparative Analysis Final Report," Rocketdyne